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Radio continuum imaging of FIR luminous QSOs at $z > 6$

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ABSTRACT

We present sensitive imaging at 1.4 GHz of the two highest redshift far-infrared (FIR) luminous QSOs SDSS J114816.65+525150.2 ($z = 6.42$) and SDSS J104845.05+463718.3 ($z = 6.2$). Radio continuum emission is detected from J1148+5251 with $S_{1.4} = 55 \pm 12\mu$Jy, while J1048+4637 is marginally detected with $S_{1.4} = 26 \pm 12\mu$Jy. Comparison of the radio and FIR luminosities shows that both sources follow the radio-FIR correlation for star forming galaxies, with implied (massive) star formation rates $\sim 10^3$ $M_\odot$ year^{-1}, although we cannot rule-out as much as 50% of the FIR luminosity being powered by the AGN.

Five bright (> 22 mJy) radio sources are detected within $8'$ of J1148+5251. This is a factor 30 more than expected for a random field. Two sources have SDSS redshifts,

including a $z = 1.633$ radio loud quasar and a $z = 0.05$ radio galaxy. However, we do not find evidence for a galaxy cluster in the SDSS data, at least out to $z = 0.2$. Considering the faint SDSS magnitudes of the remaining radio sources, we conclude that the over-density of radio sources could either be a statistical fluke, or a very large scale structure ($>$ 8Mpc comoving) at $z \geq 1$. We also consider the possibility of gravitational lensing by the closest (in angle) bright galaxy in the SDSS data at $z = 0.05$, and conclude that the galaxy provides negligible magnification.

Subject headings: radio continuum: galaxies — infrared: galaxies — galaxies: active, starburst, formation, high redshift

J114816.65+525150.2, J104845.05+463718.3

1. Introduction

We are pursuing an extensive study of the thermal dust, molecular line, and radio continuum emission properties of luminous QSOs from redshifts $z \sim 2$ into the epoch of reionization (EoR) at $z \geq 6$. One key aspect of these studies is to determine the star formation characteristics of the host galaxies. This question has become paramount since the discovery of the bulge mass – black hole mass correlation in nearby galaxies, a result which suggests a fundamental relationship between black hole and spheroidal galaxy formation (Gebhardt et al. 2000; Ferarrese & Merrit 2000). We have found that 30% of optically selected QSOs are hyper-luminous far-infrared (FIR) galaxies, with $L_{FIR} > 10^{13}$ $L_\odot$, corresponding to thermal emission from warm dust, and with dust masses $\geq 10^8$ $M_\odot$ (Omont et al. 2003; Carilli et al. 2001a; Bertoldi et al. 2003a; Priddey et al. 2003). Radio continuum studies show that most of these sources follow the radio-to-FIR correlation for star forming galaxies (Carilli et al. 2001b). If the dust is heated by star formation, the implied (massive) star formation rates are of order 10^3 $M_\odot$ year^{-1}, enabling the formation of the stellar content of a large spheroidal galaxy in a dynamical timescale of order 10^8 years, although a contribution to dust heating by the AGN certainly cannot be ruled out (see Andreani et al. 2003). Demographic studies show that super-massive black holes acquire most of their mass during major accretion events marked by the QSO phenomenon (Yu & Tremaine 2002).

Molecular line (CO) emission has been detected from 13 FIR-luminous $z > 2$ QSOs to date (see Carilli et al. 2004 for a review), including the highest redshift QSO, J1148+5251 at $z = 6.42$ (Walter et al. 2003; Bertoldi et al. 2003b). The implied molecular gas masses are 10^{10} to 10^{11} $M_\odot$. Detecting large masses of dust and CO in the highest redshift QSOs indicates that heavy element and dust formation, presumably via star formation, is a fundamental aspect of the early evolution of QSO host galaxies, right back to the EoR, within 0.8 Gyr of the Big Bang. Indeed, these observations of the dust and gas content of the highest redshift QSOs are currently the only direct probe of the host galaxies in these systems. This conclusion is supported by the super-solar

quasar metallicities deduced from the optical emission line ratios (Fan et al. 2003; Freudling et al. 2003; Maiolino et al. 2003; Pentericci et al. 2002).

In this paper we present the most sensitive radio continuum observations to date of the two highest redshift FIR-luminous QSOs known, SDSS J114816.65+525150.2 at $z = 6.42$ and SDSS J104845.05+463718.3 at $z = 6.2$ (hereafter J1148+5251 and J1048+4637). Both sources have been detected at 250 GHz (1.2 mm) using the MAMBO detector at the IRAM 30m telescope (corresponding to a rest-frame wavelength of 160μm), with flux densities of 5.0 ± 0.6 mJy and and 3.0 ± 0.4 mJy, respectively (Bertoldi et al. 2003a). Sensitive, high resolution radio continuum observations, in combination with the (sub)mm observations, potentially probe the star formation characteristics of the host galaxies (Carilli et al. 2001b). The radio observations presented herein were designed to probe to levels expected for star forming galaxies, as set by the FIR luminosities, as well as to perform wide-field imaging to study the clustering of radio sources along the line of sight to the QSOs. Clustering in the field is an important characteristic when considering the possibility of gravitational magnification of the QSO. Gravitational lensing is a key factor in the study of high-z QSO demographics, and in calculations of 'cosmic Stromgren spheres' (see discussion). We assume a standard concordance cosmology with $H_o = 70$ km s^{-1} Mpc^{-1}.

2. Observations and results

Observations of J1148+5251 and J1048+4637 were made with the VLA at 1.4 GHz in the A and B configurations (30 km and 10 km maximum baselines, respectively). The observational parameters are listed in Table 1. Most of the observations were made in standard continuum mode, except for one A array observation of J1148+5251 that was done in spectral line mode in order to perform very wide field imaging. Standard gain and phase calibration, and self-calibration, was applied, and the images were made using the wide-field imaging capabilities of the AIPS task IMAGR.

The last two columns in Table 1 give the measured flux density at the optical position of the QSO for each observation (note: in all these observations the sources are unresolved). For J1048+4637 we get a (weighted) average value of 26$\pm$12μJy. For J1148+5251 the value is 55$\pm$12μJy. Hence J1148+5251 is reasonably detected at 4.6σ, while J1048+4637 is only marginally detected at 2.2σ. The B array images of the two sources are shown in Figure 1 at 4.5$''$ resolution.

Figure 2 shows the wide field image of J1148+5251, while Figure 3 shows a blow-up of the inner part of the field, along with the SDSS optical image (the contour levels are different in the two images, in order to emphasize only the brighter sources in Figure 2). Note the large number of bright radio sources in the J1148+5251 field, in particular five sources brighter than 22 mJy within 8$'$ of the QSO. This is a factor 30 higher than the average source density for $S_{1.4} > 22$mJy (White et al. 1997). For comparison, the brightest source within 8$'$ of J1048+4637 is 11 mJy, which is roughly as expected for a random field. Four of the five bright sources are extended, double radio

sources, and one is unresolved at 1.5″ resolution. The SDSS reveals optical counterparts for all five sources (York et al. 2000; Abazajian et al. 2003). Two of the sources have spectroscopic redshifts, one corresponding to a bright QSO at $z = 1.634$. The positions and magnitudes for the five sources brighter than 22 mJy within 8′ of J1148+5251 are given in Table 2, in order of decreasing radio flux density. We note that a similar over-density of radio sources has also been found in the field around the $z = 6.28$ QSO SDSS J1030+0524 (Petric et al. 2003).

The most striking radio source is the bright FRI (Fanaroff-Riley Class I = 'edge-darkened') radio galaxy extending over 4′, with the core located 1′ southwest of J1148+5251 (source 4 in Table 2). This galaxy was also detected at 250 GHz with $S_{250} = 4 \pm 0.9$ mJy using MAMBO (Bertoldi et al. 2003a), and has an SDSS spectroscopic redshift of $z = 0.050$. The SDSS photometry implies a bolometric magnitude for this galaxy of $M_{bol} = -21.6$, or a bolometric luminosity of 3.4×10^{10} $L_\odot$. There is also a companion galaxy in the SDSS (not radio loud) at the same redshift, located 25″ northwest of the FRI host.

On seeing the over-density of bright radio sources in the J1148+5251 field, we searched the SDSS data for a galaxy cluster. No cluster of galaxies is seen within a degree of J1148+5251 out to $z = 0.2$, although a linear 'filament' is detected in the galaxy distribution that extends from about 14,000 to 24,000 km s^{-1}.

3. Discussion

3.1. Star formation and the radio-FIR correlation

The radio-FIR correlation for star forming galaxies is one of the tightest correlations in extragalactic astronomy, and has become a standard tool in the study of extragalactic star formation (Condon 1992), eg. as a fundamental assumption in the radio photometric redshift technique, widely used for distant starburst galaxies (Carilli & Yun 1999), and as a radio-loud AGN diagnostic (Reddy & Yun 2004). In this section we consider the two FIR-luminous $z > 6$ QSOs in the context of the radio-FIR correlation.

The FIR luminosities of the sources were derived from the 250 GHz flux densities by Bertoldi et al. (2003a) assuming a spectral energy distribution (SED) typical of an ultra-luminous infrared galaxy, corresponding roughly to thermal emission from warm dust at 50 K with a dust emissivity index $\beta = 1.5$. For J1148+5251 they find: $L_{\rm FIR} = 1.21 \pm 0.14 \times 10^{13}$ $L_\odot$. The value for J1048+4637 is $L_{\rm FIR} = 7.5 \pm 1.0 \times 10^{12}$ $L_\odot$.

We derive the intrinsic luminosity density at 1.4 GHz from the observed flux density at 1.4 GHz assuming a spectral index of -0.8, characteristic of star forming galaxies. For J1148+5251 we find: $L_{1.4} = 2.1 \pm 0.4 \times 10^{25}$ W Hz^{-1}, and for J1048+4637: $L_{1.4} = 9.2 \pm 4.6 \times 10^{24}$ W Hz^{-1}.

The radio-FIR correlation has been quantified via the standard q parameter, defined as (Con-

don 1992):

$$q \equiv \log(\frac{L_{\rm FIR}}{3.75 \ \times \ 10^{12} \ {\rm W}}) - \log(\frac{L_{1.4}}{\rm W \ Hz^{-1}})$$

where $L_{\rm FIR}$ is defined as the far infrared luminosity between 40 and 120 μm. For J1148+5251 we find: $q = 1.80 \pm 0.14$, and for J1048+4637: $q = 1.89 \pm 0.36$, where the errors are derived assuming $\pm 1\sigma$ errors on each quantity.

In Figure 4 we plot the q values versus 60μm luminosity[1] for J1148+5251 and J1048+4637, and for the IRAS 2 Jy sample of galaxies from Yun et al. (2001). The solid line shows the mean of the relationship for the IRAS galaxies, $q = 2.35$, while the dashed lines show the range determined by Yun et al. to correspond to star forming galaxies. Objects below this range are radio-loud AGN. Both the high z QSOs fall within the range corresponding to star forming galaxies. If star formation is the dominant dust heating mechanism in these sources, the implied star formation rates are about 3000 $M_\odot$ year^{-1} and 2000 $M_\odot$ year^{-1}, respectively (Bertoldi et al. 2003b).

Of course, we cannot rule-out some contribution to dust heating by the AGN. For instance, the sources could still fall in the range defined by star forming galaxies (ie. $q > 1.6$) and yet have 30% to 50% of their FIR luminosity powered by AGN dust heating. Likewise, current constraints on the rest-frame IR SEDs cannot preclude a warm ($>$ 100K) dust component, presumably heated by the AGN, that would dominate in the mid-IR, as has been seen in the cloverleaf QSO at $z = 2.558$ (Weiss et al. 2003).

The radio-FIR correlation provides a consistency check for star formation in the host galaxies of these systems, although it should not be construed as proof thereof. Coupled with the large molecular gas masses, the fuel for star formation, these observations argue for a massive starburst coeval with the accretion activity onto the supermassive black hole in these systems. High resolution imaging of the CO emission is in progress which should help elucidate the characteristics of the host galaxy (Walter et al. 2004).

3.2. Gravitational Lensing of J1148+5251

Strong gravitational lensing would magnify these sources, such that the inferred luminosities would be over-estimated. The intrinsic luminosity is one of the key parameters in the calculation of the radii of cosmic 'Stromgren spheres' around these sources, which can be used to constrain the timescale for QSO activity, or alternatively, the neutral fraction of the IGM (Haiman & Cen 2002; White et al. 2003; Wyithe & Loeb 2004). Lensing corrections are also fundamental to the derivation of QSO demographics (Wyithe & Loeb 2002; Fan et al. 2003; Yu & Tremaine 2002;

[1] For the assumed SED the 60μm luminosity (νL_ν) is 2/3 the FIR luminosity.

Richards et al. 2004).

Although there is a clear over-density of bright radio sources in the J1148+5251 field, no galaxy cluster is seen in the SDSS data out to $z = 0.2$. Two of the radio sources have spectroscopic redshifts ($z = 0.05$ and $z = 1.6$). If we assume that the radio sources without spectroscopic redshifts have host galaxies with luminosities similar to that of the $z = 0.05$ source, then their faint optical magnitudes place them at $z \sim 1$ to 1.5. Hence, it is possible that these three sources, plus the QSO, form a large scale structure at $z \sim 1.6$. However, the angular separation of the sources implies a scale for such a structure ≥ 8 Mpc (comoving), ie. not a dense cluster. We conclude that the over-density of bright radio sources in the J1148+5251 field is either a statistical fluke, or a very large scale structure possibly at $z \sim 1.6$. Such filamentary structures on very large scale lack the mass surface density to produce strong gravitational magnification (Bacon et al. 2001).

We also consider lensing by the brightest galaxy closest to the line-of-sight to the QSO at $z = 0.05$ (source 4 in Table 2). From the observed magnitude we calculate a velocity dispersion of 275 km s^{-1} for this galaxy using the Faber-Jackson relation. The magnification of the QSO $1'$ distant from the galaxy is then negligible (roughly 5%).

Overall, the radio and SDSS data provide no evidence for a dense cluster, or bright galaxy, along the line of sight to J1148+5251 which could act to magnify the QSO. Of course, these data cannot rule-out a much more distant galaxy, or cluster, close to the line of sight lensing the QSO. White et al. (2003) consider this question in detail, and in particular, they discuss evidence for a possible 'proto-cluster' at $z \sim 5$, as suggested by Ly α emission and CIV absorption in the QSO spectrum. They conclude that such a distant cluster could magnify substantially the QSO without violating the size constraint of 0.4" set by ground-based near-IR imaging (Fan et al. 2003). HST imaging at 0.1" is in progress which will test this interesting possibility (White et al. in prep). We note that HST images of four other $z > 5.7$ QSOs by Richards et al. (2004) show no evidence for multiple imaging on scales of 0.1".

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Table 1. Observational Parameters

Source	Date	Config.	Mode	Bandwidth	Time	Frequency	FWHM	$S_{1.4}$	rms
				MHz	hours	MHz	arcsec	μJy	μJy
J1048+4637	June 20, 2003	A	Continuum	2×50 MHz	2	1385, 1465	1.5	28	19
J1048+4637	Jan 17, 23, 2004	B	Continuum	2×50 MHz	2×5	1385, 1465	4.5	26	13
J1148+5251	June 20, 2003	A	Continuum	2×50 MHz	2	1385, 1465	1.5	46	20
J1148+5251	Sept 19, 2003	A	Line, 8chan	2×25 MHz	8	1365, 1435	1.5	57	18
J1148+5251	Jan 16, 2004	B	Continuum	2×50 MHz	4	1385, 1465	4.5	67	27

Table 2. Radio sources brighter than 22 mJy within 8′ of J1148+5251

	Position (J2000)	r[a]	$S_{1.4}$	z
	h m s, d m s	mag	mJy	
1	11 48 56.57, +52 54 25.3	16.57	100	1.633
2	11 48 16.10, +52 58 59.2	20.38	98	
3	11 48 19.59, +52 52 12.3	20.62	84	
4	11 48 12.19, +52 51 07.5	14.70	56	0.050
5	11 47 59.11, +52 55 42.8	20.42	22	

[a]Model magnitudes from the Sloan Digital Sky Survey (York et al. 2000; Abazajian et al. 2003).

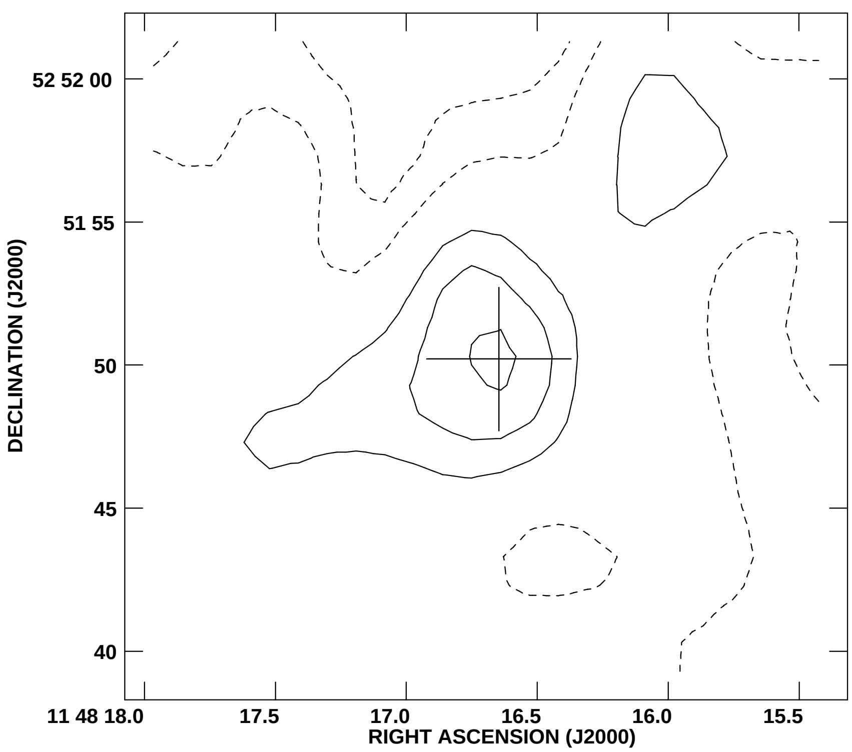

Fig. 1.— VLA image of the SDSS J1148+5251 at 1.4 GHz at 4.6″ resolution (FWHM). The contour levels are –52, –26, 26, 52, 78 μJy beam^{-1}. The QSO position is indicated by a cross.

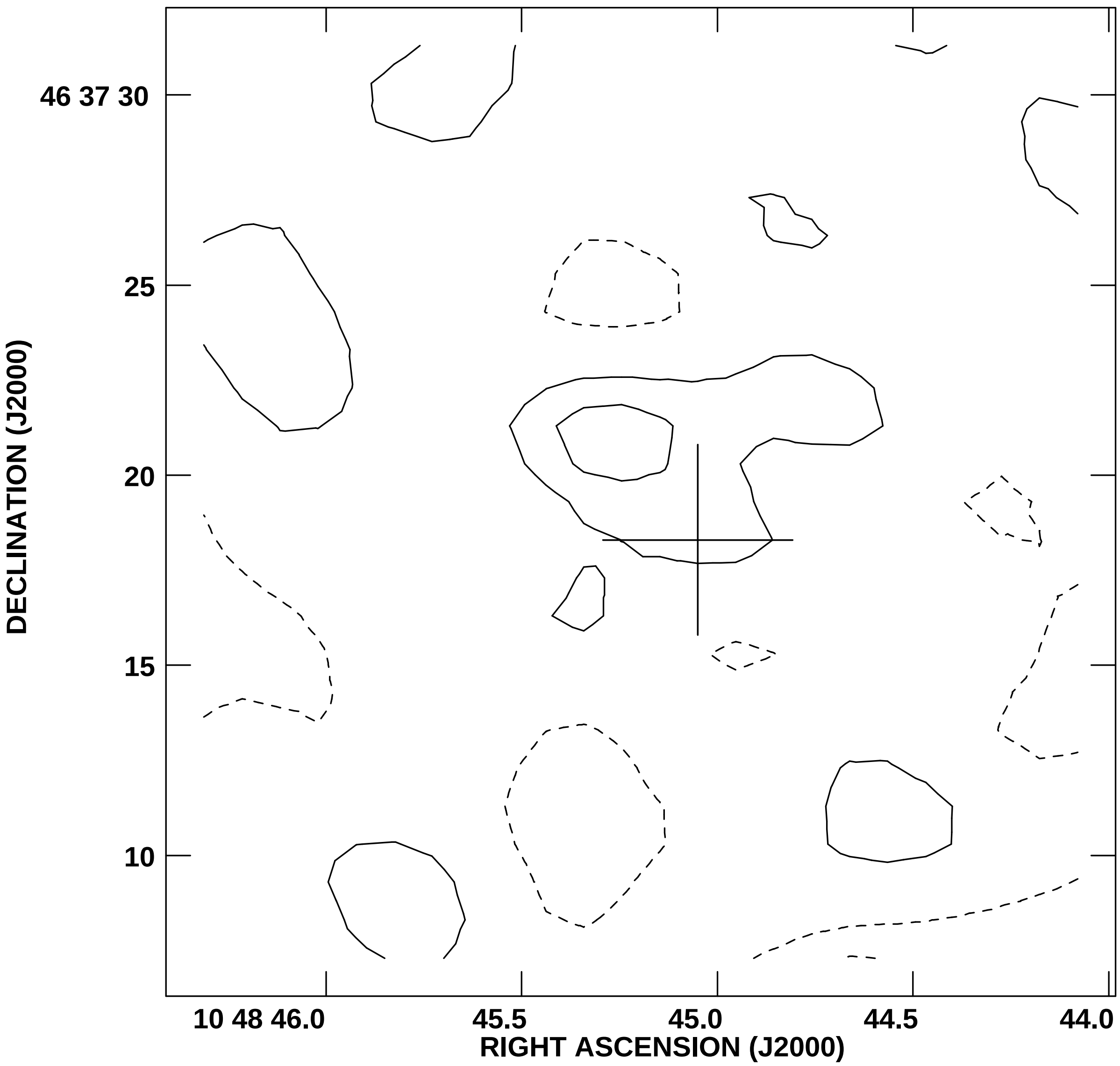

Fig. 2.— VLA image of the SDSS J1048+4637 at 1.4 GHz at 4.6″ resolution (FWHM). The contour levels are –36, –18, 18, 36, 54 μJy beam^{-1}. The QSO position is indicated by a cross.

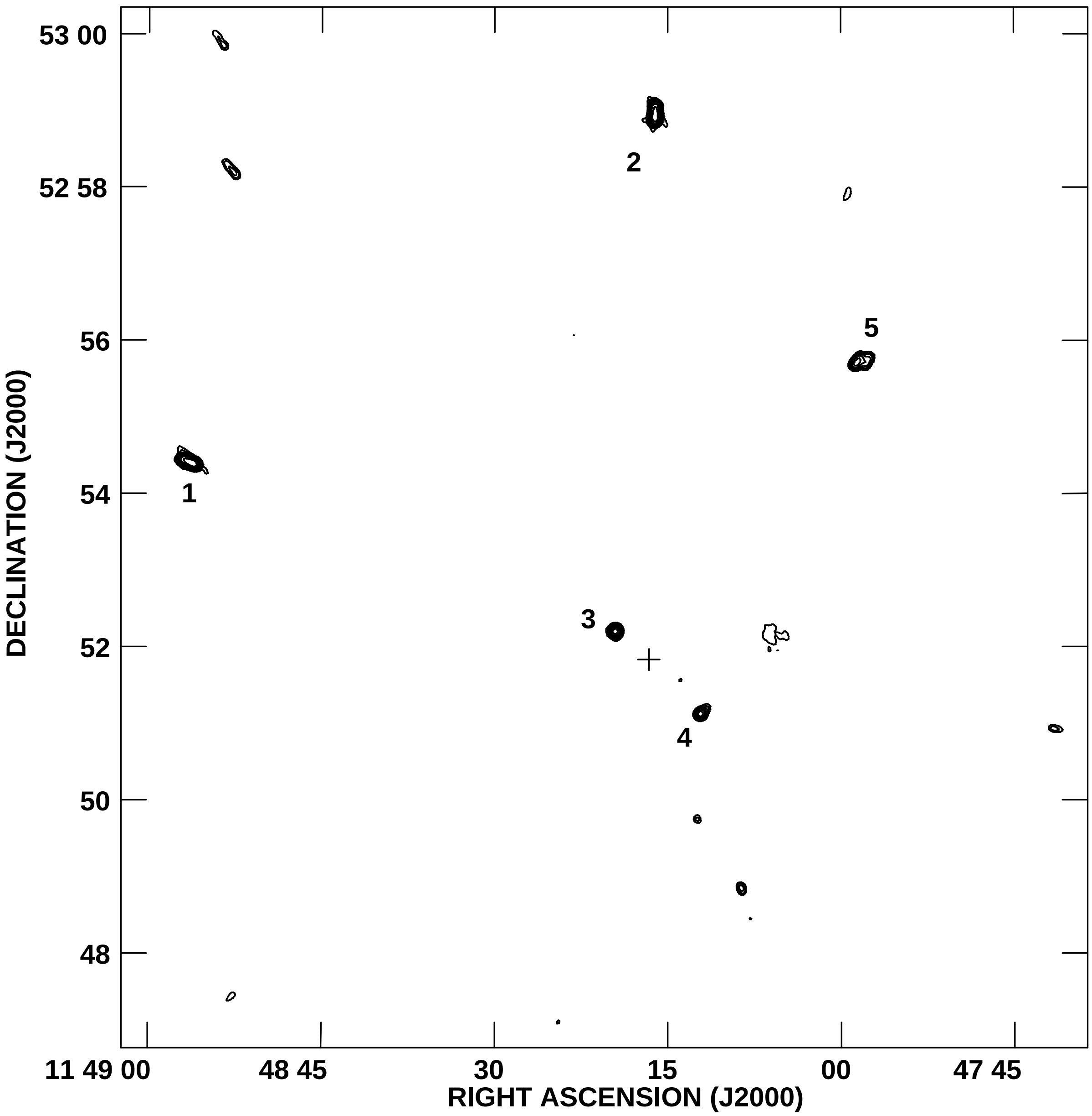

Fig. 3.— VLA image of the SDSS J1148+5251 field at 1.4 GHz at 4.6″ resolution (FWHM). The contour levels are a geometric progression by a factor of two, starting at 0.2 mJy beam^{-1}. The QSO position is indicated by a cross. The elongation of the outer-most sources ($\geq 6'$ from the QSO) is due to bandwidth smearing.

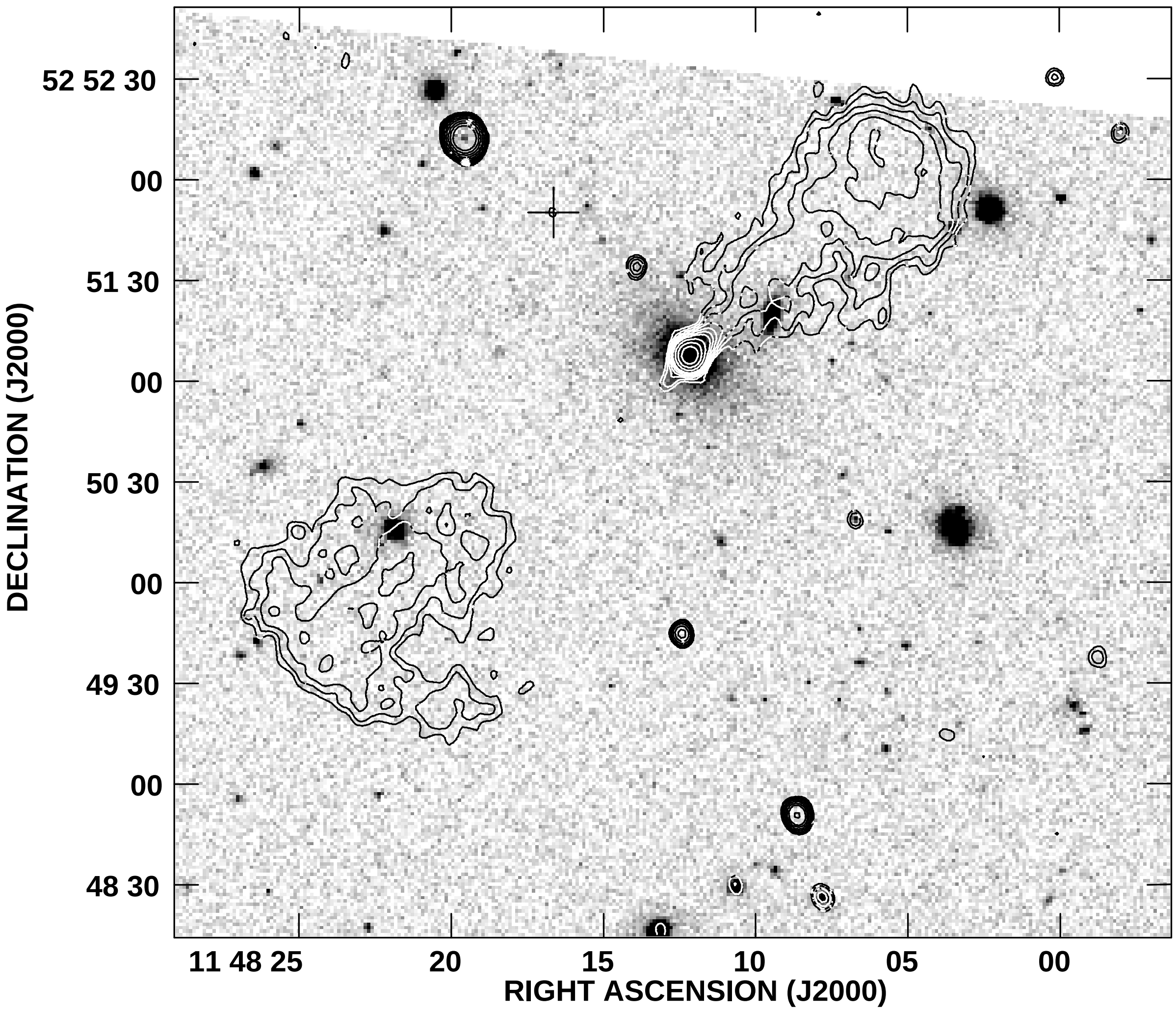

Fig. 4.— VLA image of the inner part of the SDSS J1148+5251 field at 1.4 GHz at 4.6″ resolution (FWHM). The contour levels are a geometric progression by a factor of $\sqrt{2}$, starting at 0.075 mJy beam^{-1}. The QSO position is indicated by a cross. Note that the contour levels go to lower levels than in Figure 1, in order to emphasize the extended structures of the radio galaxy 1′ southwest of the QSO. The grayscale is the SDSS image (York et al. 2000; Azabajian et al. 2003).

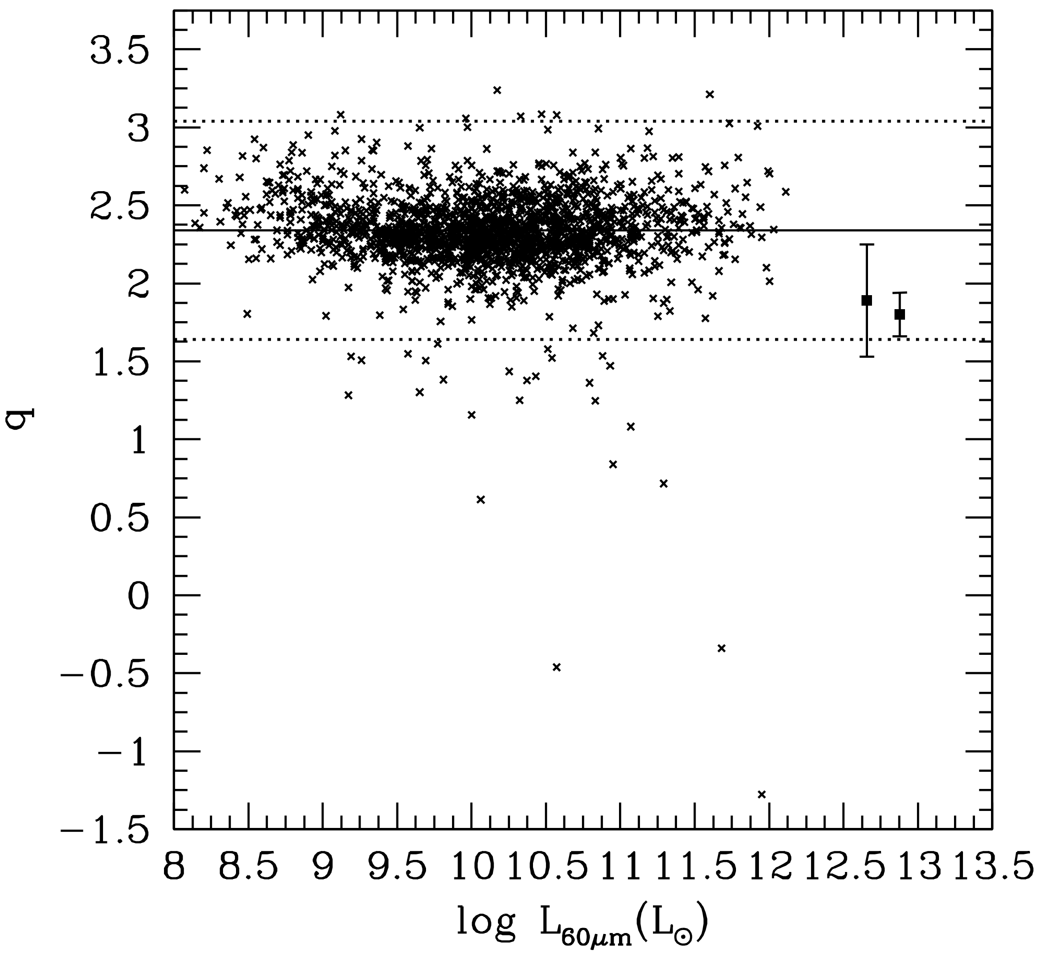

Fig. 5.— The radio-FIR correlation for the IRAS 2Jy galaxy sample (x) from Yun et al. (2001), and for J1148+5251 and J1048+4637 (points with error bars). The q parameter and $L_{60\mu m}$ are defined in section 3.1. The solid line is the mean value for the IRAS galaxies, and the dotted lines indicate the range defined as star forming galaxies by Yun et al. (2001).